Quantifying the risks of climate change on inland waterway transport in the Netherlands

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Abstract

In a series of stress tests, the robustness of the inland waterway transport infrastructure within the Netherlands to climate change is studied. The performance of the system under low flow and high flow conditions results in (1) lower available draught due to limited water depth, (2) longer levelling time due to insufficient water availability at locks, and (3) a lower number of container layers due to limitations in the clearance height at bridges. For inland shipping in the Netherlands, the stress test on the limitations on draught showed to have the largest economic consequences to the costs of transport over water.

1. Introduction

Inland waterway transport (IWT) forms an important contribution to the transport of cargo in the Netherlands. Of the total freight transport, approximately 34% is transported over water. IWT in the Netherlands uses a combination of shipping canals and rivers that have been normalised and canalised for improved inland navigation.

The Dutch trajectory of the river Rhine is a free-flowing river, and forms a major shipping route from the Port of Rotterdam to Germany with a fairway width of at least 150 m. The river is normalised by the construction of groynes and the removal of sharp bends. On a daily basis an average of 400,000 tons is transported over this route. The water levels are still susceptible to discharge variations and may limit IWT due to insufficient water depth (low flow) or insufficient clearance height (high flow).

The Dutch trajectory of the river Meuse is strongly canalised with the construction of lateral canals and weirs, and locks to pass these weirs. This shipping route is used primarily for national IWT, but also offers a connection to the Belgium network. All year, the water levels are controlled by the weirs, allowing sufficient water depth in the fairway. However, during low flow periods, the discharge in the Meuse is no longer sufficient to freely operate the locks, resulting in additional operational measures.

It may be clear that the discharge on the Rhine and Meuse is of importance for a reliable inland fairway network. As a result of climate change the discharge regimes of both rivers are expected to change. Thus, climate change may form a risk on the future reliability of inland navigation.

To gain insight into the current and future state of the system, the programme “Climate Resilient Infrastructure Networks” was set up by the Dutch government within the national programme on spatial adaptation. One of the focus fields is the Inland Fairway Infrastructure (only those managed by the national government). The goal of the programme is to determine vulnerabilities, discuss with stakeholders and to set up a future agenda. In a series of stress tests, the effects of amongst others low flow and high flow are evaluated.

This paper will discuss three of those stress tests by making use of future climate change scenarios:

- The effects of low flow on a free-flowing river (on the Rhine)
- The effects of low flow on the operation of locks (on the Meuse)
- The effects of high flow on the clearance height at bridges

In all stress tests we quantified the effects for the inland waterway transport sector. Novel methods are set up using computational and analytical models. Each section can be read individually and is based on research from multiple reports.

All stress tests make use of future climate change scenarios for the years 2050 and 2085. Based on the global IPCC reports, the Royal Netherlands Meteorological Institute (KNMI) made a translation of climate change projections for the Netherlands. These KNMI ’14 scenarios (Figure 1) are used to derive future river discharge series. Based on these scenarios, in other projects of Deltares a permutation of a 100-years discharge timeseries is made. Based on these discharge scenarios characteristic statistical years are developed for this paper that schematise a drought year with a return period of 1, 2, 10 and 100 years. This action is performed for scenarios G_L and W_H and for both the year 2050 and 2085 (De Jong, 2019; De Jong 2020a).

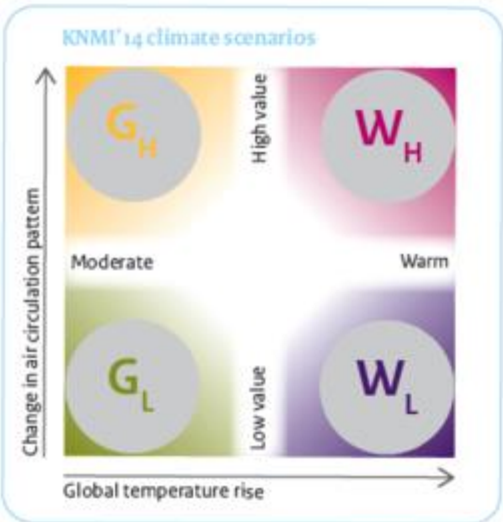

Figure 1: Climate scenarios by the KNMI (KNMI, 2015).

2. Stress test on the effects of low flow on the Rhine

2.1 Introduction

The draught of vessels on the river Rhine ranges between 1 and 4 m, with a median of around 2.5 m. During low flow conditions, the water depth is insufficient for all vessels to sail with their preferred draught and as a result the cargo (or load factor) need to be reduced to decrease the ship’s draught. The remaining cargo is transported with additional ships or with other modalities, resulting in higher transport costs. When this is no longer possible, the cargo is no longer transported resulting in larger economic consequences. In this study this increase in transport costs due to drought is quantified (De Jong & Van der Mark, 2021; De Jong, 2020b).

2.2 Method

To quantify the effects of low flow on the shipping sector in the current and future climate, a combination of models was set up.

Step 1: Modelling the water depth in the fairway of free-flowing rivers

Computing the water depth in the free-flowing rivers requires knowledge on the state of the river and the water discharge. The state of the river is continuously changing. Human interventions such as the construction of river engineering measures to improve flood safety and ecological quality of the river are executed every year. Most famous are the measures in the programme Room for the River (in Dutch: Ruimte voor de Rivier), which also include measures within the main channel of the river that influence the flow conditions during low flow. The Dutch government actively invests in the modelling of the accurate state of the river in different hydraulic models. This paper uses the one-dimensional (1D) SOBEK model which is also calibrated on low flow conditions. Models of the Rhine, Meuse and Rhine-Meuse-delta are merged into a combined model shown in Figure 2. Boundary conditions include the river discharge of the Rhine and Meuse and an average tidal boundary at the North Sea. As low flow conditions often coincide with drought, a major part of the river discharge is distributed to canals to assure amongst others the water quality in these canals. An estimate for each of those extractions is included in the model.

Figure 2: River branches in the combined 1D SOBEK model of the Maas/Meuse, Rijn/Rhine and Rijn-Maasmonding/Rhine-Meuse-delta. Several other locations that are mentioned later in this paper are also included.

For modelling future scenarios, it is required to include the ongoing trend in bed erosion and sedimentation in the model. These trends influence the discharge distribution over the Rhine branches and influence the water depth, especially around non-erodible bed layers in both the main channel and at locks. Measurements have shown that over the last 20 years local trends are averaging between –1.8 cm/year to +1.8 cm/year (Ylla Arbós, 2019). Based on these trends, scenarios are developed for the expected bed level in 2050, including the change in trend that can be observed or is to be expected (Sloff, 2019). For the Waal Branch (the main branch of the Rhine River) the trend is shown in Figure 3. The estimated future trend is imposed on the main channel of each cross-sectional profile as demonstrated in Figure 4.

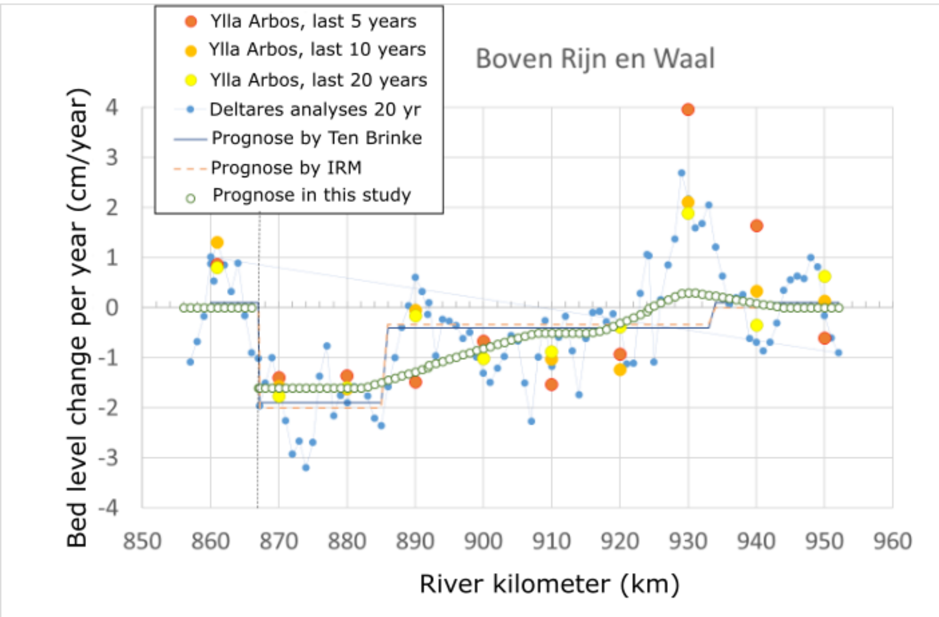

Figure 3: Bed level change along the river Rhine from measurements as analysed by Ylla Arbós (2019) and the expected future bed level change applied in this paper (green dots).

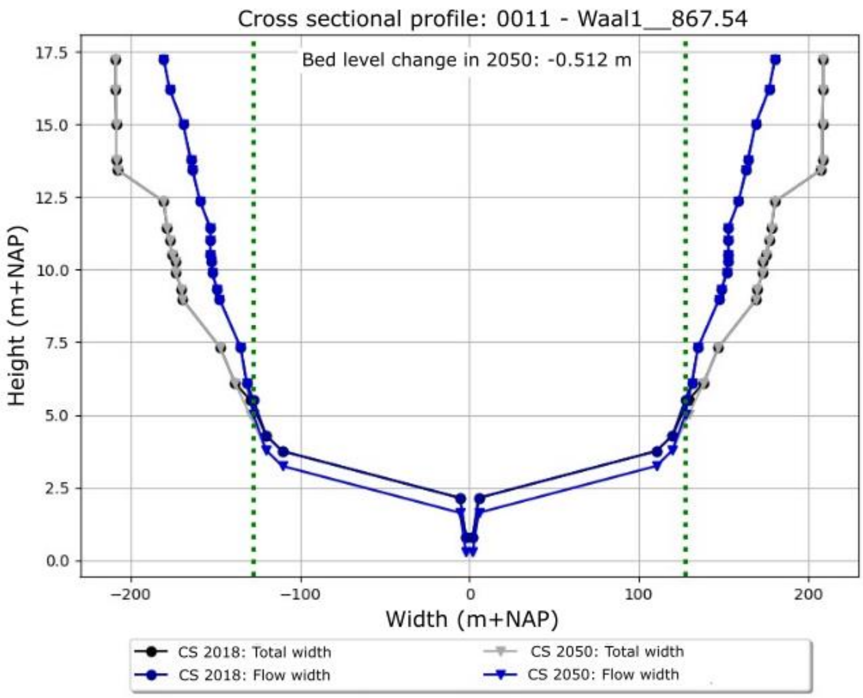

Figure 4: Example of a cross-section on the Rhine where for the situation of 2050 the main channel (between the green lines) is corrected with a bed level trend of –0.512 m.

The cross section as shown in Figure 4, also demonstrates that the main channel in the 1D model is a strong simplification of reality. The schematisation is created by analysing the bed level over a stretch of 500 m, computing the bed level volume and translating this into the cross-sectional profile. In this process any information on river bedforms and shallow inner river bends is lost. However, this information is critical for an accurate water depth in the fairway. The water depth is therefore computed by imposing both the measured bed level and the computed water levels on a two-dimensional (2D) grid and analysing this grid to find the best available fairway. A grid is constructed following the main channel with approximate cell width of 10 m and cell length of

300 m. To construct a bed level grid, in each grid cell the 95% percentile highest value of all measurements (resolution of 1x1 m) is used as the normative bed level (Figure 5). Using this process, the anomalies in the samples are filtered out while the effect of bedforms and shallows remains. The water level results of the SOBEK model are linearly interpolated to this grid. Subtraction per cell of water and bed level results in a 2D grid of the water depth.

The water depth grid is analysed for the deepest available fairway. The minimum required width of each fairway stretch is defined by governmental regulations (Koedijk, 2020). By interpolating the grid for a given channel width, the available water depth is found. However, during low flow conditions, the channel width may be reduced to allow for saver navigation and larger water depth. This is most apparent on the river IJssel, where the smallest sections are only 40 m. To take this into account in the grid, the interpolation is extended with a module where the required width can be slightly relieved when the minimum required depth (2.5 or 2.8 m) can no longer be obtained. A demonstration of this process is given in Figure 6.

The resulting water depth of this step forms the building block for the shipping analyses.

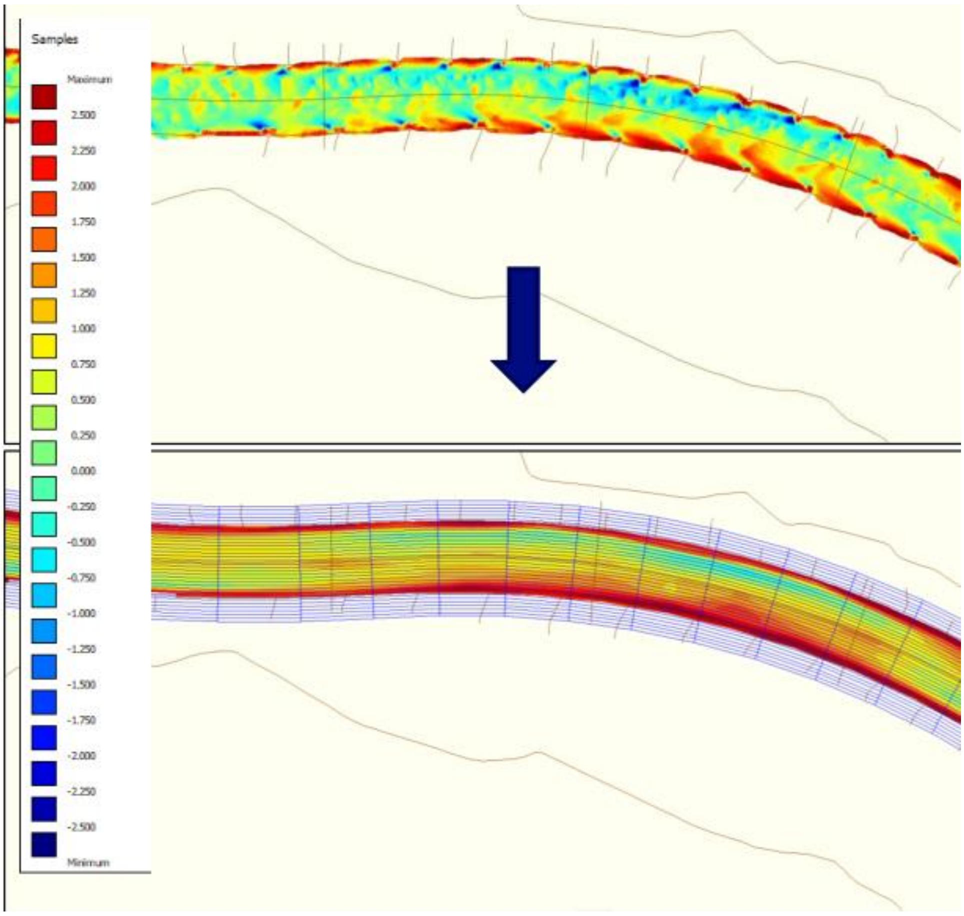

Figure 5: Process of transposing the high-resolution samples onto the bed level grid for a stretch of 3 km on the river Waal.

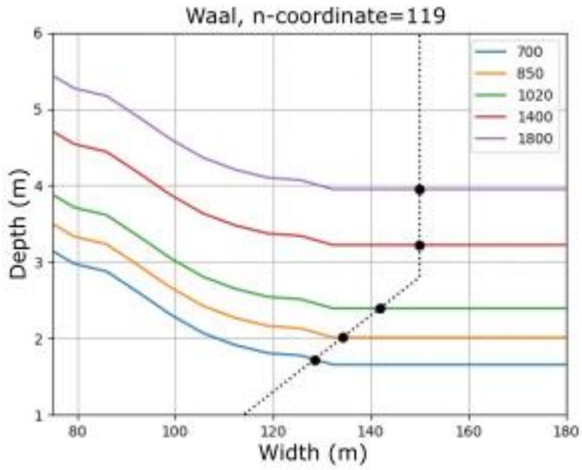

Figure 6: Example of the water depth as a function of the channel width for different discharges (coloured lines) for an arbitrary cross-section on the Waal River. The dashed line indicates the minimum required width-depth combination. The crossings of the lines (black dots) give the resulting depth and width of the fairway channel.

Step 2: Modelling the effect of low water depth on the shipping sector

The effect of limited water depth on the shipping sector is computed by the numerical model BIVAS (Inland shipping analysis system, in Dutch BInnenVaart Analyse Systeem). This model is maintained by the Dutch government and contains a schematisation of all fairways in the Netherlands as well as important reaches in neighbouring countries (Figure 7). The network is schematised with arcs between all ports and bifurcations. To each arc, the shallowest cross-section from the water depth grid is attributed, as well as flow velocities coming directly from the SOBEK model. This coupling is shown in Figure 8.

Another core component of the BIVAS model is a dataset of all annual trips over the network. The registration service IVS is used to develop this dataset. Each of the over 400,000 individual trips has unique information on amongst others the origin, destination, ship draught, cargo and the ship type. The registrations of the year 2014 are used as the reference situation with good sailing conditions during the entire year. We make use of this reference situation, as well as a future situation with economic growth.

During a run, the BIVAS model will find the cheapest way to transport the cargo over the network. The model (including corrections in the post-processing) will find the most efficient route and if necessary reduce the draught of the vessel. When the draught needs to be reduced, the reduction in cargo is computed using the metric TPCMI (Tons per centimetre immersion) of that specific vessel. It is assumed that the total transported cargo is to be kept constant, resulting in an increase in the number of trips. For example, if the cargo of a trip is reduced by 20%, it is assumed to increase the trips by 25%. Accordingly, all metrics of this trip are corrected by a factor 1.25. This is shown in the example in Figure 9.

The most important metric is the variable sailing costs, consisting of costs for fuel, staff, insurance, interest, depreciation and maintenance. Each ship type has unique parameterisation to compute these costs from research by Panteia (2018).

Additionally, a correction is performed for the situation where reduction of cargo is more than 80%.[1] In this case it is assumed to be no longer profitable for inland waterway transport. It is assumed that

[1] All post-processing scripts are available on https://github.com/jurjendejong/pyBIVAS

depending on the type of cargo, transportation will be either delayed or carried using a different modality. To simplify this economic analysis, it is assumed that the costs remain at the level costs of 80% cargo reduction (an increase of 400% with respect to the sailing costs without limitations in draught). In the figures this is referenced to as the costs for not-transported cargo.

Figure 7: Fairways in the BIVAS model for the year 2030. The network extends with European waterways outside this figure.

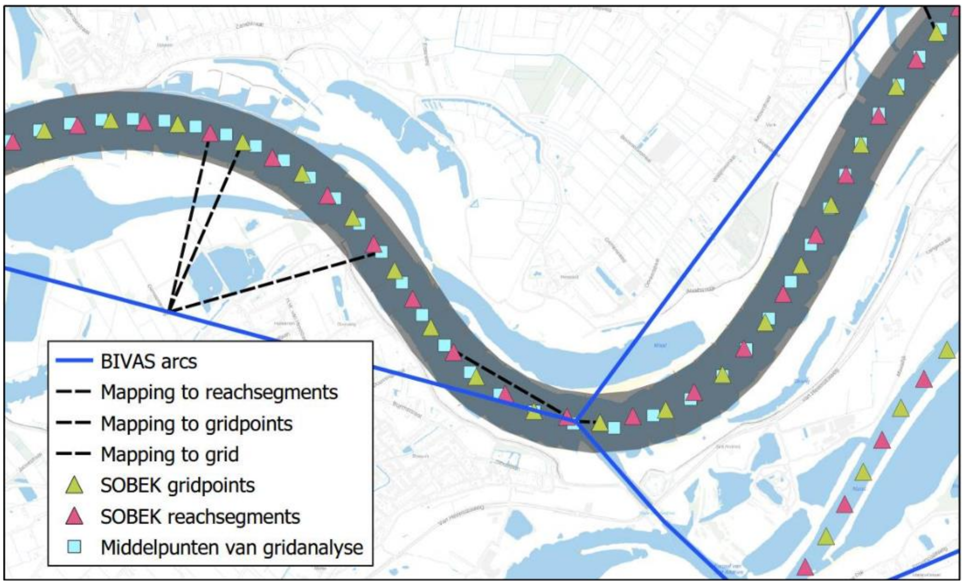

Figure 8: Example of a close-up of the arcs in the BIVAS model, and the coupling that is developed to the water depth grid and the SOBEK model.

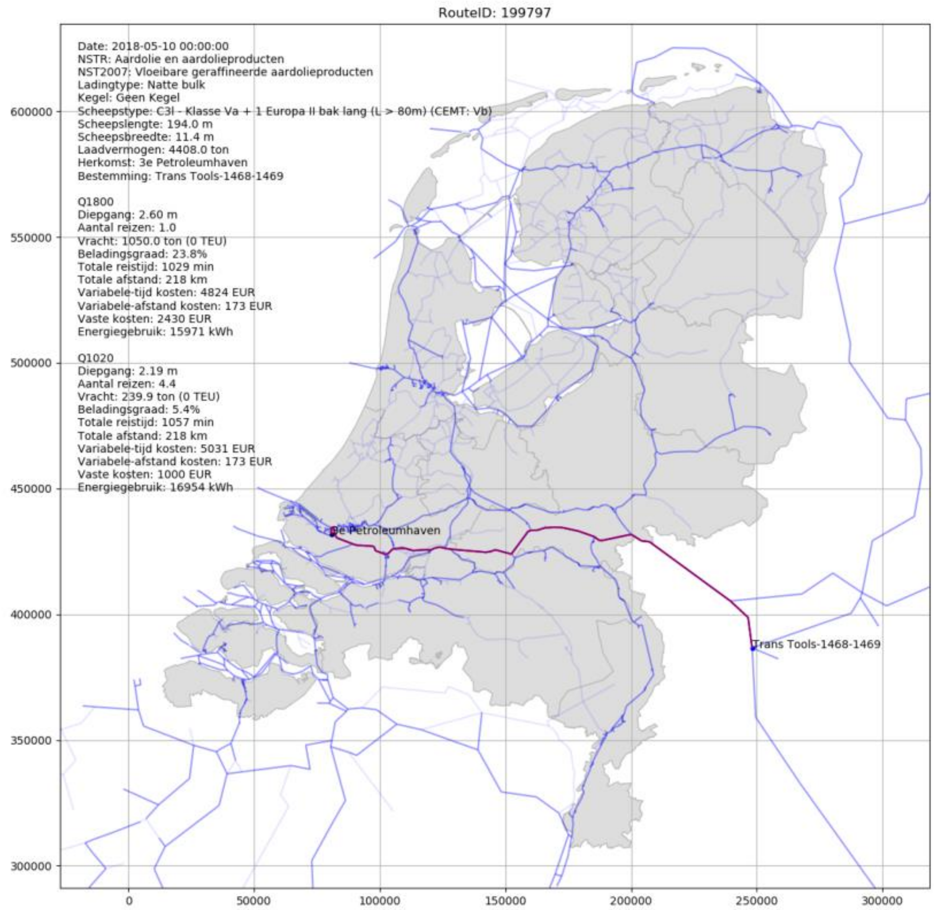

Figure 9: Example of a single trip as computed by BIVAS. The top block shows details on this trip from the IVS database, the second block and third block show trip details when the discharge on the Rhine is respectively 1800 and 1020 m³/s. The different components are written in the figure in Dutch, but they give an indication of the extensiveness of the IVS database and the result of the BIVAS simulations.

2.3 Results

Results look both at the state of the fairway under climate change, as well as the consequences on the IWT. A selection of the results is given in the figures below. Figure 10 shows that at a very low discharge of 700 m^3/s, the transport costs of the IWT sector increase by 3 million euro per day with respect to the average of 6.3 million on a day without draught limitations. Figure 11 shows that in a dry year (a long period of low discharge) with a return period of 10 years (T10), the total transport costs can increase with 126 million euro. In a scenario with high climate change (KNMI scenario W_H), the costs in a T10 dry year increase to 263 million euro. Averaged over a longer period these costs are lower: 48 million euro per day in the current climate, and 104 million with high climate change. Please note that the costs calculated are pure transportation costs; additional costs and cascading damage are not accounted for.

Using the results, it is discussed to what extent measures can be achieved to increase the state of the fairway. An increase in water depth in the order of 10 cm can be achieved with river engineering measures. For example, by construction of longitudinal training walls, as recently realised as a pilot on the river Waal. However, these measures cannot fully counteract the loss in water depth as a result of climate change.

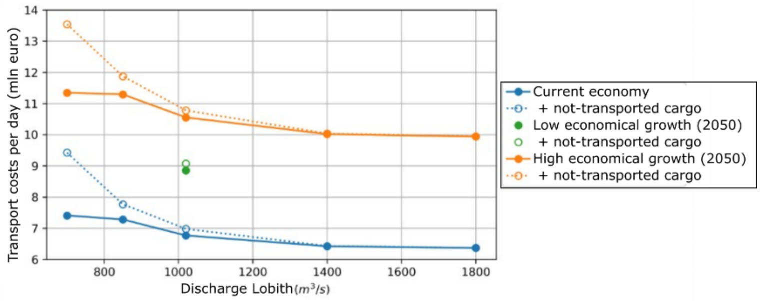

Figure 10: Total transport costs of the IWT in relation to the discharge on the Rhine at Lobith (at the Dutch German border). An assumption is done for the costs for the cargo that cannot be transported over water.

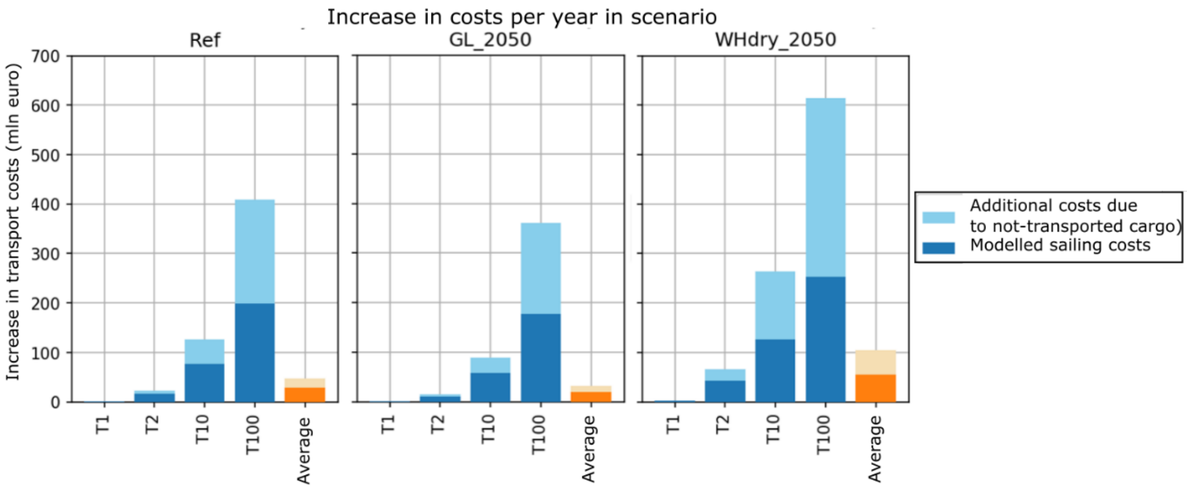

Figure 11: Increase in transport costs in low discharge years with a return period of 1, 2, 10 and 100 years, and the yearly average over a long time. For the reference scenario (left) and a scenario with moderate climate change (centre) and high climate change (right). These costs in a year without drought problems are approximately 2 billion euro. An assumption is done for the costs for the cargo that cannot be transported over water.

3. Stress test on the effects of low flow at locks on the Meuse

3.1 Introduction

The river Meuse is strongly canalised by the construction of weirs in both the Netherlands and Belgium. In the most upstream reach of the Netherlands, the Julianakanaal is constructed as a parallel canal to the Meuse (this reach of the Meuse is called the Grensmaas, a Nature 2000 area). The large head of the locks in this canal (up to 11.85 m) results in a significant water demand for lock operation. From discharge measurements it is shown that on average 17 m^3/s is required to operate the canal. However, during low flow conditions, the total discharge of the Meuse can fall below 25 m^3/s, which requires sparingly operation of the lock to save sufficient water for the Nature 2000 area and other users of the Meuse water.

The water demand of the levelling process can be reduced with a number of operational measures:

- Reducing the number of levellings by requiring a higher occupancy rate of the lock chamber (gentle or strict regime)
- Using pumps to return the water to the upstream canal
- Saving water in the levelling process by using a water basin or by siphoning between lock chambers.

Each measure results in an increase in the operational costs, either by increasing the energy demand of the locks (when using pumps) or due to the increase in passage time of the vessels due to the longer waiting or levelling times (all other measures). To verify the reduction in water demand, Figure 12 shows the statistical relation between the discharge on the Maas and the discharge towards the locks. During low flow on the Maas, the water demand by the lock reduces from 17 m^3/s to below 5 m^3/s. However, a strategy is required on when to use which one of these measures such that it results in the lowest total costs. In this stress test (De Jong & Boschetti, 2020) different strategies are developed for each of the lock complexes. This also shows the annual damage as a result of drought, and the possible mitigation when installing additional infrastructure.

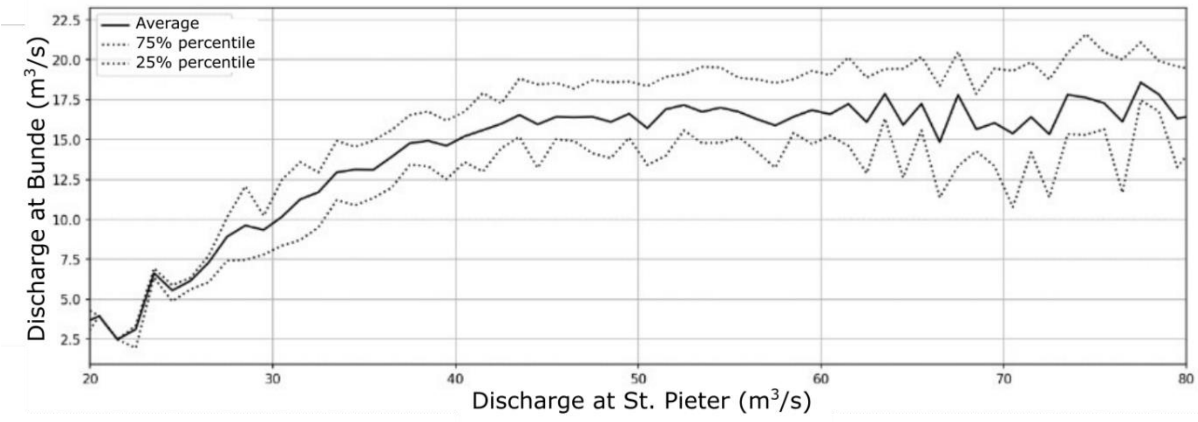

Figure 12: Analyses of discharge measurements from 1999 to 2018. The x-axis shows the discharge on the Meuse (at St. Pieter), the y-axis shows statistics (mean, and 25% and 75% percentile) of the discharge towards the locks (Julianakanaal at Bunde).

3.2 Method

To compute the water usage per strategy, the numerical model SIVAK is used to compute the number of levellings, supplemented with analytical models to calculate the corresponding water demand.

SIVAK III, developed by Systems Navigator for the Dutch government, is an agent-based model, where the lock operation (see Figure 13) is modelled for a given network (a lock complex with a few km of canal on both sides) and a given ship demand (all registered passages in a normative week). The model decides when levelling should be initiated based on three given criteria: actual fill ratio of chamber with ships, potential fill ratio due to waiting ships at the other side of the lock, and a maximum waiting time for passing vessels. The outcome of the model is the passage time per ship and the number of levellings. By varying the levelling criteria, different outcomes are obtained.

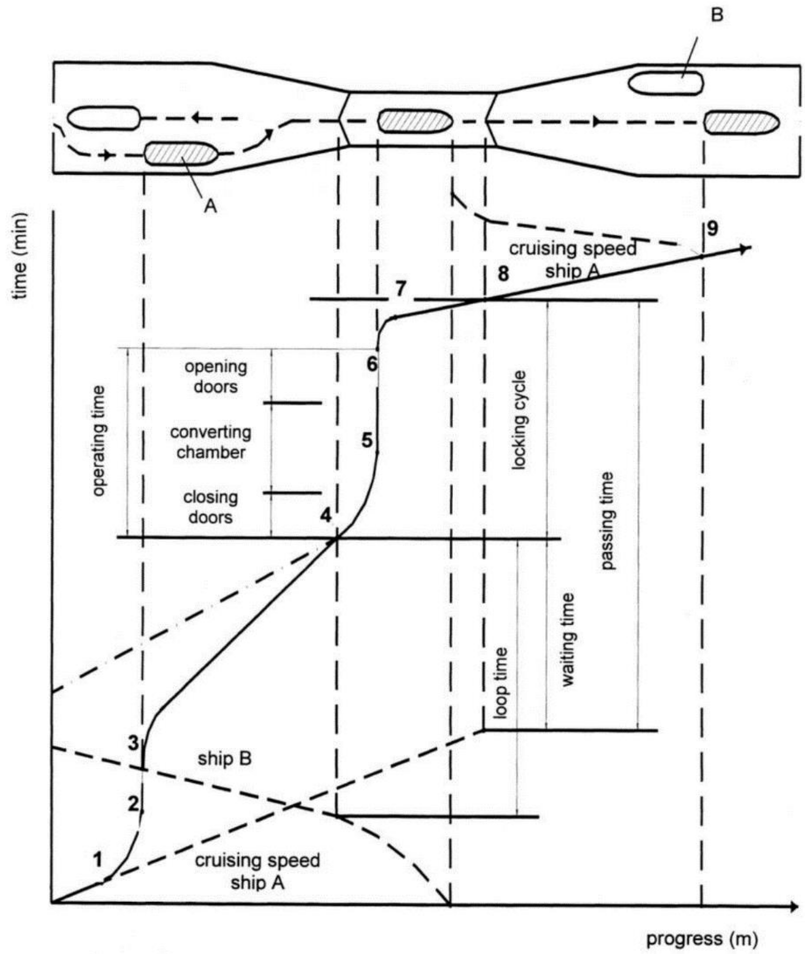

Figure 13: Space-time diagram of a levelling procedure (from Groeneveld, 2006)

By post-processing these results[2], the costs in euros and the total water demand are calculated. The costs for the shipping sector are quantified by multiplying the additional waiting time with the costs per hour of that specific vessel type (on average 70 euro per hour, Panteia, 2018). The additional costs of operating the pumps varies between 0.004 and 0.005 euro per m^3.

Also, the water demand is computed by substantial post-processing. The levelling time from SIVAK cannot be combined with the effect of siphoning. Therefore, the exact times are computed with analytical models and linked to the model outcome. The basis of the levelling times is on observations, but this is alternated for siphoned levelling with the use of analytical models. This analytical model takes the dimensions of the siphons and basins, but also includes the criteria to which level the siphoning is operated.

[2] Post-processing scripts available on https://github.com/jurjendejong/pySIVAK

3.3 Results

The results for three types of individual measures are given for the lock complex at Maasbracht in Figure 14. The figure shows the costs and discharge for the reference situation (green) and the effect of change in levelling regime, siphoning between locks and the use of pumps. It can be concluded that as a first measure to reduce water demand, pumps would be the most expensive solution (the steepest line). The levelling regime is relatively cheap when going for a gentle regime, but when trying to save more water with a stricter regime if discharge drops further, the costs steeply increase. The siphoning is a relatively cheap solution and can save up to 6.5 m^3/s.

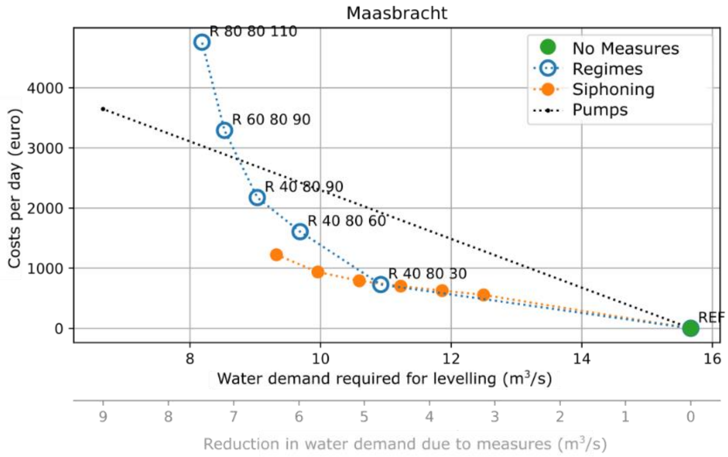

Figure 14: Effect of a levelling regime (blue), the use of siphoning between lock chambers (orange), or the use of pumps (black).

Based on those results a strategy with minimized costs is developed as given in Figure 15. The figure shows the discharge that is available for the locking process and the water that can be saved by using siphoning, levelling regime or pumps. The figure to the right gives the corresponding costs for these measures. In this strategy, at first the siphoning is fully activated resulting in higher costs for the shipping sector (longer passage times), for discharges lower than 9 m^3/s the (gentle or strict regimes) are partly initialised, and for discharge below 6.5 m^3/s the pumps are used for the additional savings among with more strict levelling regimes. The distinction between costs for the manager and for the shipping sector led to challenges in the optimisation. In the final result as given in Figure 15 the measures are chosen such that all costs above the dashed lined are split equally between both parties.

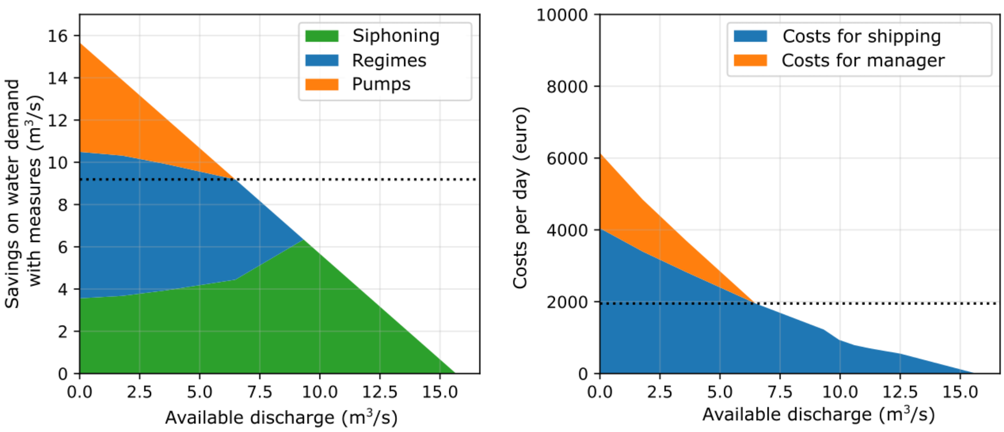

Figure 15: Water saving strategy for lock Maasbracht. For each available discharge (horizontal axes), water saving can be achieved by any of the three given measures: siphoning (green), levelling regimes (blue) and using pumps (orange). The right figure shows the resulting costs in this scenario, split by costs for the manager of the locks (orange) and for the shipping sector (blue).

Combining the discharge series for the climate scenarios with the costs at each discharge level, results in the total costs in those characteristic years as given in Figure 16. In very dry years in the current climate with a return period of 10 years, the additional costs due to drought are modelled at 145,000 euro, in the climate change scenario WH this increases to 502,000 euro. However, these years are very seldom and the average annual costs are lower: 80,000 euro in the current climate and 230,000 in scenario Wh 2050.

Although these costs can be further lowered with infrastructural adjustments, the research showed that the required investments would probably be higher than the net present value of the savings.

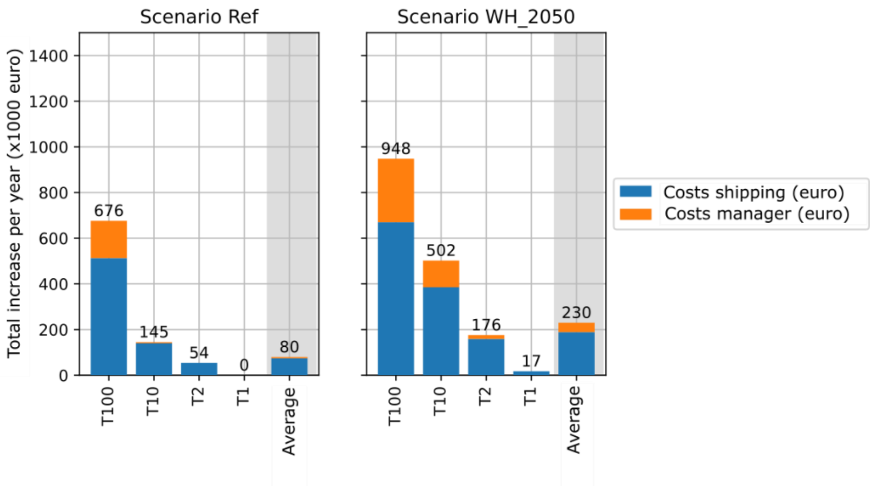

Figure 16: Additional costs at the lock at Maasbracht as a result of the drought with a return period of 100, 10, 2 and 1 year.

4. Stress test on the effects of high flow on clearance height

4.1 Introduction

The final stress test included in this paper, is research on limitations in clearance height during high flow conditions (Van der Wijk & De Jong, 2021). The clearance height is used by container vessels to determine the number of layers of containers on their trip. During periods of higher discharge, the number of layers might need to be reduced as a result of low clearance height at one or multiple bridges along the route.

In this stress test it is evaluated which bridges on the route are most limiting in height. By combining this with discharges in different climate change scenarios and a dataset of all vessel types, it is calculated how often these bridges are limiting and for how many vessels.

4.2 Method

A dataset is used of all bridges over the Dutch rivers. The basis of this dataset is formed by the Fairway Information System (FIS)[3], but manual adjustments are performed to have a more accurate indication of the bridge height for each bridge.

Similar to the earlier stress tests, the basis of the analyses is formed from the time series of the daily-average discharge over 100 years. However, the statistical analysis is adjusted now to result in characteristic years for a given return period based on the years with the highest discharge.

[3] Publicly available on https://vaarweginformatie.nl/

For each discharge the water level at each bridge is calculated from a dataset of earlier performed model simulations (this product is called “Betrekkingslijnen 2020-2021"). Subtracting the bridge height with the water level results in the available clearance height, as indicated in Figure 17.

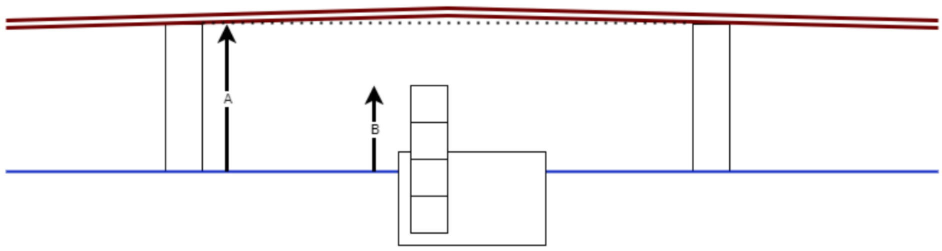

Figure 17: Sketch of a container vessel with 4 container layers under a bridge. Indicated with arrows are the available clearance height (A) and the required clearance height (B).

A vessel dataset is obtained from a model run on the annual IVS-registrations with BIVAS (see also earlier introduction in section 2.2). For each bridge in the network, a query is performed to get a dataset of all vessels that passed this bridge over a year. The IVS registrations contain the number of containers per vessel but does not contain an accurate estimate of the height of the vessel and the number of layers of containers.

Using the formulae below, the containers per layer are estimated from the Length (L) and Width (W) of the container vessel. The total height of the vessel above water (H) can now be calculated based on the number of containers (n), the height per container layer of 2.896 m (Hn), the vessel’s draught according to IVS (D), the vessels bottom thickness of 0.5 m (Hb) and a safety margin of 0.3 m (Hs). It should be noted that all these dimensions are based on the assumption that all containers are high cube containers. Although in practise many transported containers are still the conventional height of 2.59 m, the exact distribution is not known. By using high cube containers in the formulae, a conservative approach is used. An example of the distribution in container vessels on the Rhine at Nijmegen is shown in Figure 18.

$$containers\ per\ layer = \frac{(0.9 \cdot L - 10)}{6.2} \cdot \frac{W - 1.5}{2.45}$$

$$H = n \cdot H_n - D + H_b + H_s$$

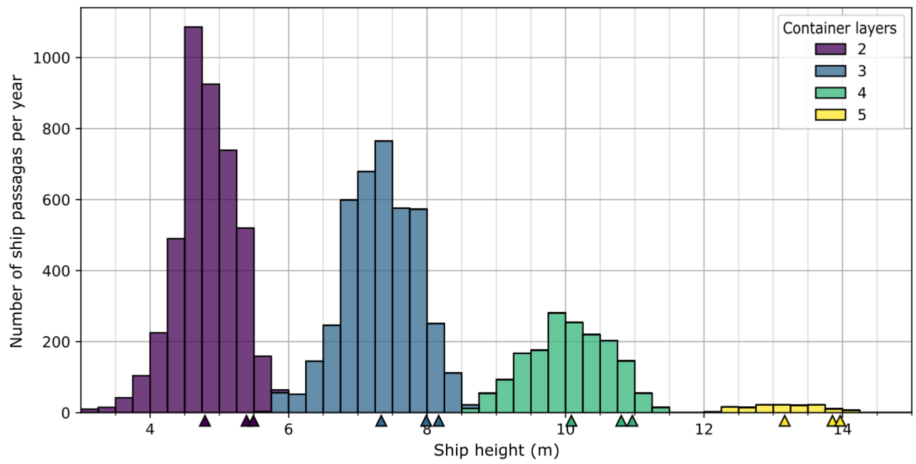

Figure 18: Distribution in ship height at Nijmegen (Rhine) based on the IVS data in BIVAS and the formulae above. The indicators on the x-axis mark the 50%, 90% and 95% percentile of the height for the given number of container layers.

A model is set up where the distribution of required clearance height is compared to the available clearance height for a given river discharge in the climate change scenarios.

4.3 Results

The results of the clearance height analyses for the Rhine are summarised in Figure 19. It shows the clearance height at the normative bridge on each branch of the Rhine. Typical heights that are often indicated as norms for container transport are 11.35 m and 9.1 m. In this figure we read that at the Prins Willem-Alexanderbrug on the river Waal, a height of 11.35 m is not available for 8 days a year, but that this might increase to 15 days due to climate change (scenario Wh 2085). During a year with a once-in-10-years high discharge, this height is not available for 22 days and this might increase to 32 days due to climate change. A height of 9.1 m is nearly always available on the Waal. However, on the river IJssel the available clearance height is substantially lower and is below 9.1 m for over 70 days per year in the current situation.

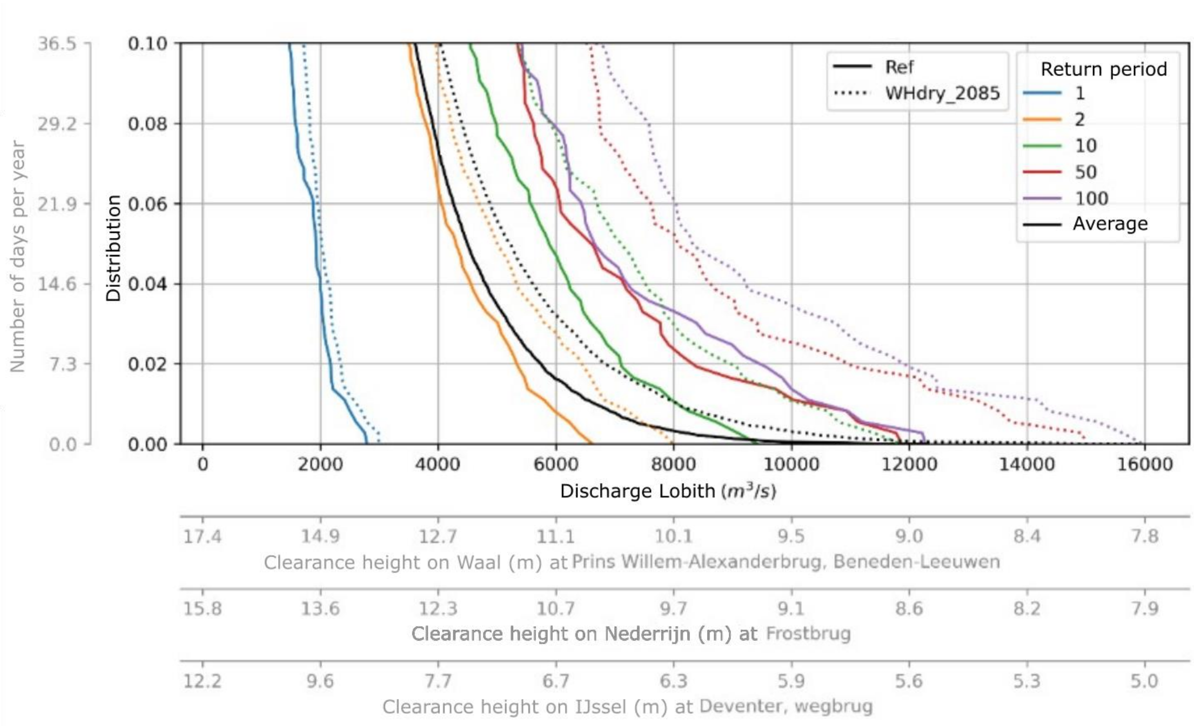

Figure 19: Distribution curve of the discharge on the Rhine at Lobith in an average year (black line) and in characteristic years with high discharge. For each discharge the secondary x-axis shows the bridge with the lowest clearance height on the major branches of the Rhine (respectively Waal, Nederrijn and IJssel)

By comparing the available height (Figure 19) with the required height (Figure 18) it is calculated how much the container transport is reduced as a result of the insufficient height. It is concluded that in an average year, the capacity is lowered by 1300 TEU as a result of high discharge. This may increase to 2200 TEU as a result of climate change (WH 2085). Compared to the total transport of 2 million TEU on the Waal this is approximately 0.1%.

4.4 Discussion

The research shows that high discharge events only have impact on the number of container layers on a very limited number of vessels. In essence, the current standards for bridge height on the Rhine in the Netherlands result in such high bridges that the height of these bridges is hardly ever the limiting factor in the available clearance height. Nearly always, elsewhere on the route (i.e., outside the Netherlands) the bridges are lower. In many cases this involves the (lower) bridges on the Rhine in Germany. It is worthwhile to further discuss the necessity of the currently high bridge design standards (De Jong & Van der Wijk, 2021).

5. Conclusions

From the research on climate resilient infrastructure, it is concluded that climate change has the largest effect on the inland shipping on free-flowing river Rhine. The resulting risks and costs in the stress tests on clearance height and at locks are significantly lower. Although this is known from practise, the stress test has allowed to quantify the direct costs to the shipping sector as a result of the low flow. The annual costs from drought are calculated at 48 million in the current climate and an increase to 104 million as a result of climate change (scenario W_H in 2050). From an economic perspective it is important to know the year-to-year variation in costs. The costs in a year with probability of occurrence of once every 10 years, are calculated at 126 million in the current climate and can increase to 263 million as a result of climate change.

The reliability of the Rhine as a major transportation route is at stake. Considering the ambition of the European Union to increase the inland waterway transport, this poses a challenge to the realisation of a resilient fairway.

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